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Modelling Of An Electric Vehicle Using PMSM Motor With Field Oriented Control Strategy

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Abstract:
This research paper focus on modelling of an Electric Vehicle using Field-Oriented Control (FOC) which is a highly effective technique for enhancing the performance of Permanent Magnet Synchronous Motors (PMSM) in electric vehicles (EVS), where over the past few decades, global warming has become a major global concern although different green energy policies are being formulated and implemented by government. Hence, a comprehensive simulation model of a rear-wheel-drive EV is developed using MATLAB/Simulink, where a PMSM serves as the propulsion system. The model includes detailed vehicle dynamics, enabling the calculation of total tractive effort based on vehicle mass, road load forces, and rotational inertia. These parameters are used to determine the total torque demand required for acceleration and overcoming resistive forces. The study presents an in-depth analysis of FOC implementation for PMSMS in EVS, emphasizing both motor control and vehicle-level performance.
Keywords: *Vehicle, Field Oriented Control (FOC), Permanent Magnet Synchronous (PMSM), Indian Drive Cycle (IDC)*

1. INTRODUCTION:

The transport industry is the primary source of global warming, with China emitting about 25% of greenhouse gases, followed by the USA (13.87%) and India (7.45%). EVs are transforming the transportation industry. The advantages that electric vehicles (EVs) provide to society are immense. The main advantages include low operating costs, energy efficiency, and simple integration with renewable energy sources, in addition to a notable decrease in carbon emissions [1]. Electric vehicles represent a transformative shift in the global transportation landscape, offering an innovative and sustainable alternative to traditional ICE vehicles. EVs are at the forefront of addressing environmental challenges such as climate change, urban air pollution, and reliance on fossil fuels. Reasons why electric motors are replacing ICEs is that electric motors are more economical than ICE, electrical motors are generally 95% more efficient than ICEs. Motors are light weighted, small in structure, and cheaper to manufacture. They are also capable of offering instant and consistent torsion at any speed. EVs power train infrastructure is a sophisticated integration of key components such as the motor, motor controller, battery, battery management system, and vehicle interface units. At the heart of the drivetrain, the motor converts electrical energy into mechanical motion, with the motor controller precisely regulating its speed and torque to optimize performance and efficiency [2]. The battery serves as the energy source, requiring a robust BMS to monitor parameters such as voltage, current, and temperature, ensuring safety and prolonging battery life. Vehicle interface units act as the communication bridge between various subsystems, facilitating seamless coordination of components. Together, these elements enable reliable operation and integration with external infrastructure for charging and grid interaction, making EVs a sustainable and efficient mobility solution. Permanent Magnet Synchronous Motors (PMSMS) have emerged as a key technology in electric vehicle (EV) propulsion systems due to their superior efficiency, high torque density, and excellent dynamic response [3]. A pivotal factor in harnessing these advantages is the implementation of Field-Oriented Control (FOC), an advanced control technique that enables independent regulation of torque and magnetic flux. By converting stator currents from the stationary to the rotating reference frame, FOC precisely aligns the stator and rotor magnetic fields, thereby optimising torque generation. It also facilitates field weakening, allowing PMSMS to operate efficiently at high speeds beyond their rated base speed [4]. FOC has significantly improved the performance of PMSMS across diverse applications [5]. In industrial automation, FOC-driven motors are utilised in systems such as conveyor belts, CNC machines, and robotics, where fast dynamic response and precise torque control are essential [6]. In robotics, they enable complex and accurate actuation for high-precision tasks. In EVS, FOC enhances both torque responsiveness and energy efficiency, meeting the demands of modern driving conditions [7].

2. SYSTEM MODELING

To effectively simulate and analyse the behaviour of EVS powered by PMSMS, it is essential to integrate vehicle body modelling into the system design. Vehicle body modelling allows for the calculation of various resistive and driving forces that influence the performance and energy consumption of the vehicle. These forces are mentioned below. The block diagaram of the proposed system is shown in Figure 1.

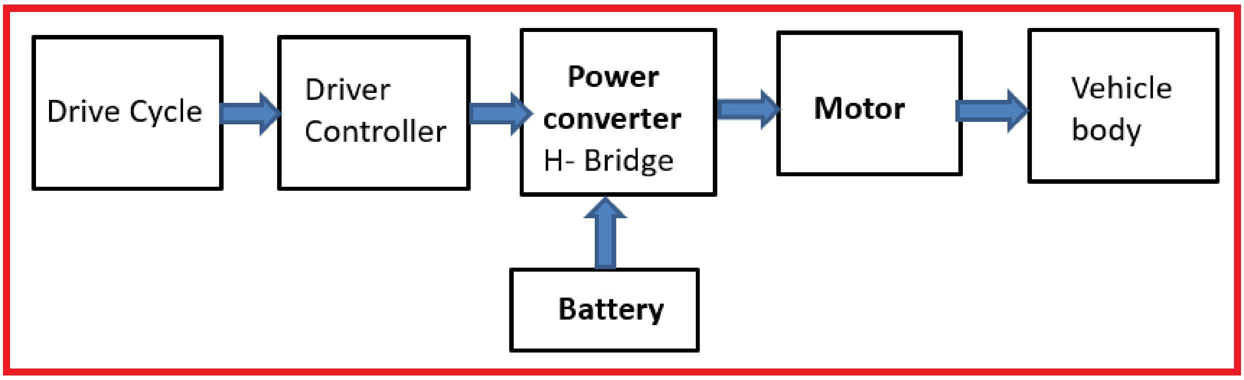

Fig 1: Block diagram of the proposed system

Aerodynamic Drag Force: This force works against the motion of the vehicle and grows with the square of the speed and is expressed as (1).

$$F_{aero} = (1/2)\, \rho\, C_d\, A_f\, v^2 \quad (1)$$

Where ρ is air density, C_d Is the aerodynamic drag coefficient, A_f Is the vehicle's frontal area, and v is the vehicle speed.

Rolling Force: This force develops against rolling resistance and is given by (2).

$$F_{roll} = C_r\, m\, g \quad (2)$$

where C_r Is the rolling resistance coefficient, m is vehicle mass, and g is gravitational acceleration.

Gradient (Hill Climbing) Force: The force required to move the vehicle up an incline and can be calculated by using equation (3).

$$F_{grade} = mg\sin(\theta) \quad (3)$$

Where θ is the angle of the road slope.

Inertial or Acceleration Force: -Reflects the force needed for acceleration and given by equation (4)

$$F_{inertia} = ma \quad (4)$$

Where a is vehicle acceleration.

Total Tractive Force: - The total force required to move the vehicle is the sum of all resistive forces and it can be calculated by using equation (5).

$$F_{tractive} = F_{aero} + F_{roll} + F_{grade} + F_{inertia} \quad (5)$$

Total Power Requirement: -The power required to drive the vehicle at a given speed is given by equation (6)

$$P_{total} = F_{tractive}\, v \quad (6)$$

Parameter	Value	Unit
Vehicle mass	1480	Kg
CG height	254	Mm
Drag coefficient	0.8	-
Front axle	1.5	M
Front area	2	m2
Rear axle	1.4	M

Air density	1.1	kg/m3
Velocity	80	Kmph
Tire b	10	-
Tire c	1.9	-
Tire d	1	-
Tire e	0.97	-
Tire rad	0.3	M
Tire inertia	1e-3	kg*m2
Rolling Resistance coefficient	0.0005	-

Table 2: Vehicle Parameters

As per the vehicle data listed in the Table -1, the forces were calculated as follows

Rolling Resistance Force R_r:

Mass*C_{r_r} = 1480*9.8*0.005 = 72.52 N

Aerodynamic Force A_r $= 0.5\rho C_d A V^2$

= 0.5*1.1*0.8*2*22.22*22.22

= 123.43 N

Total Tractive Force = $R_r + A_d$

= 72.52+123.43 =196 N

Total Power, $T_{tf}V$ = 507*22.22 =4.22 KW

Torque on wheel: $T_{tf}r$ = 196*0.3 =57.1 N

3. FIELD-ORIENTED CONTROL

The proposed electric vehicle (EV) drivetrain control system is designed based on a Field-Oriented Control (FOC) strategy for a Permanent Magnet Synchronous Motor (PMSM) and tested under the Indian Drive Cycle (IDC) to get feedback on the real-world driving conditions is shown in Figure 2. The Indian Drive Cycle Block contains a time-sensitive velocity profile representation of acceleration, deceleration and cruising behaviour typical in Indian traffic scenes. The velocity profile is used as input into Overview of the system the Driver Model, which contains Acceleration and Braking logic to replicate the driver behaviour. The output of the Driver Model is that the reference d-axis and q-axis currents (id_ref and iq_ref) are determined, which imply the desired flux and torque-producing components of the motor current. These current references are fed into a PI Controller that checks against the actual motor feedback currents (id, iq) and determines the best-fitting voltage reference (V_d and V_q for motor control. They are then converted from the rotating reference frame (dq0) to the stationary frame through the Inverse Park Transformation (FIFG) (this is necessary for connecting to the next block, the Space Vector/Pulse Width Modulation (SVPWM) unit) [8]. The SVPWM algorithm efficiently generates three-phase pulse-width modulated signals required for controlling the 3-phase Voltage Source Inverter (VSI) [9-10]. The VSI converts the DC supply of the Battery into variable-frequency and variable-amplitude AC signals required for the PMSM.

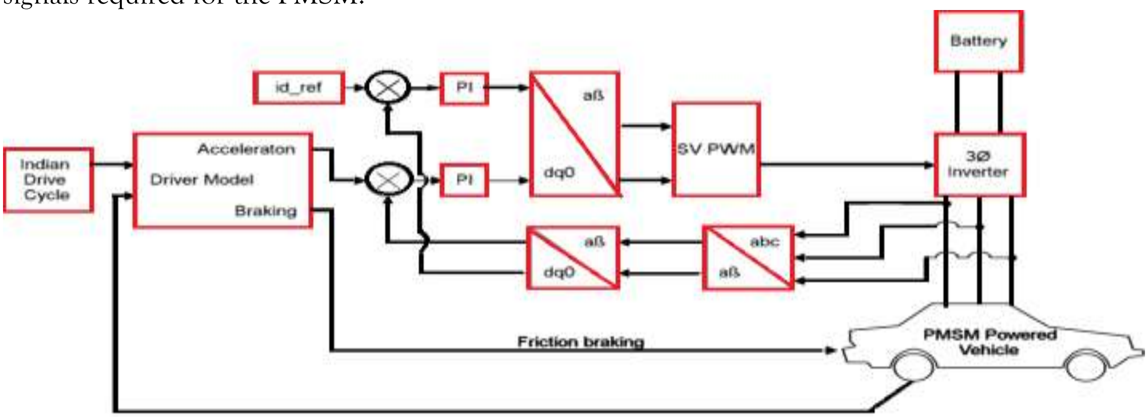

Fig.2: Block diagram of Field-Oriented Control

The output of the inverter is fed to the PMSM (motor phase currents), which converts the electrical energy into mechanical torque to drive the vehicle. The phase currents (ia, ib, ic) are measured and converted to dq0 Transformation (Clarke and Park transformations) using the rotor position is carried out to get the actual id and iq values, which closes the feedback loop by returning the currents to the PI controller for exact current regulation. The whole system is controlled as a closed-loop control scheme to ensure accurate torque and speed control of the PMSM under different drive conditions [11-12]. The model includes all the essential components such as drive cycle modelling, driver behaviour emulation, vector transformations, PWM-based inverter control and feedback regulation. This provides a broad platform for performance analysis and optimisation of EV powertrains under real traffic environments. Field-Oriented Control (FOC) system for a Permanent Magnet Synchronous Motor (PMSM) is common in electric vehicles propulsion.

The Field-Oriented Control of PMSM involves the following steps:

Step 1: Measurement of Motor Signals

- Measure the three-phase stator currents ia, ib, ic
- Measure or estimate the rotor position θ (using a position sensor or observer).

Step 2: Clarke Transformation

Convert the three-phase currents into a two-axis stationary reference frame (α-β axes):

$$i_\alpha = i_a$$
$$i_\beta = \frac{1}{\sqrt{3}}(i_a + 2i_b)$$

Step 3: Park Transformation

Transform the α-β currents to a rotating reference frame (d-q axes), using the rotor angle θ.

$$i_d = i_\alpha \cos(\theta) + i_\beta \sin(\theta)$$
$$i_q = -i_\alpha \sin(\theta) + i_\beta \cos(\theta)$$

Step 4: Current Regulation (PI Control)

- Use PI controllers to regulate the d-axis and q-axis currents:
- Set i_d=0 (no field weakening for surface PMSM).
- Control i_q based on torque demand.
- The controller output v_d, v_qvoltages.

Step 5: Inverse Park Transformation

- Convert the control voltages v_d, v_q back into the stationary reference frame:

$$v_\alpha = v_d \cos(\theta) - v_q \sin(\theta)$$
$$v_\beta = v_d \sin(\theta) + v_q \cos(\theta)$$

Step 6: Inverse Clarke Transformation

- Transform vα, vβ into three-phase voltages:

$$v_a = v_\alpha$$
$$v_b = -\frac{1}{2}v_\alpha + \frac{\sqrt{3}}{2}v_\beta$$
$$v_c = -\frac{1}{2}v_\alpha - \frac{\sqrt{3}}{2}v_\beta$$

Step 7: Pulse Width Modulation (PWM)

- The three-phase voltages are used to generate PWM signals for the inverter.
- The inverter then supplies the controlled voltage to the PMSM.

4. SYSTEM SIMULATION

4.1 Overview of the system

The system shown is a regulatory feedback loop of a PMSM motor drive in FOC configuration that manages torque and speed using FOC and SVPWM control is shown in Figure 3. The parts make coordinate frame transformations, manage current loops, and perform PWM signal generation for motor driving inverter circuitry [13-14].

4.2 Longitudinal Driver Block

Inputs need to be given are vel ref (velocity reference), vel fb (velocity feedback). The block serves as the vehicle's longitudinal controller by calculating the required torque based on manual or autonomous control. The value for the q-axis current, which directly determines the torque output (i_{dref}). Set value of d-axis current, which is usually idle (0) for efficiency optimisation (i_{qref}).

4.3 PID Controllers

The controller helps to control the closed loop to execute purely on set control parameters, i_q and i_d. It minimises the discrepancy between actual (i_q, i_d) and set-reference (i_{qref}, (i_{dref}) currents. Also, establishes proper torque control and fast, agile response. Voltages as output in dq frame are generated.

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4.5 dq to Alpha-Beta (Inverse Park Transformation)

It changes the voltage signals from the rotating dq frame to the stationary αβ frame. In stationary frames, inverters operate, so changes to the frame are required.

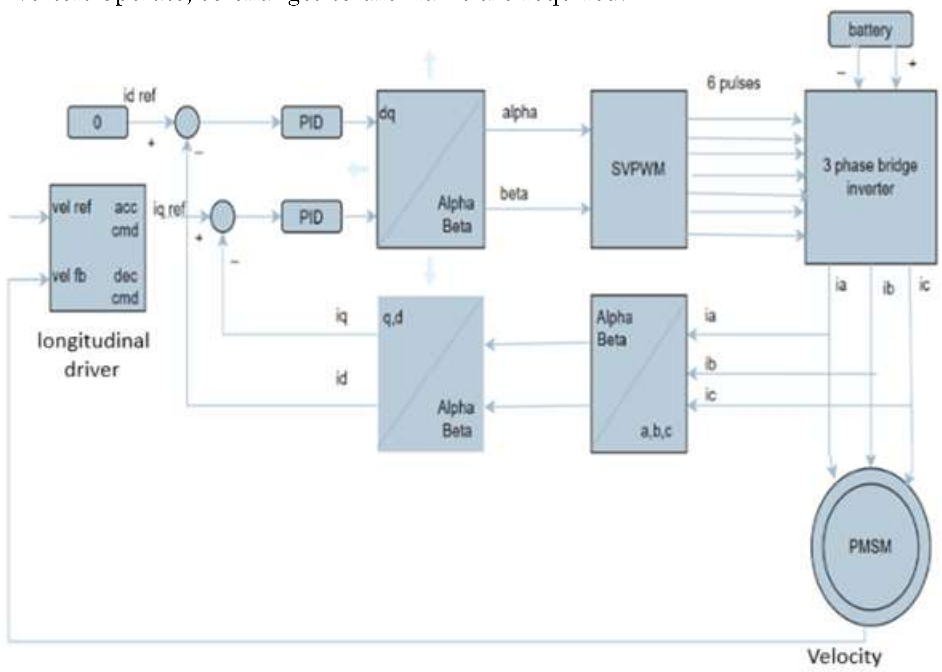

Fig.3: Feedback loop of a PMSM motor drive

4.6 PMSM (Permanent Magnet Synchronous Motor)

It helps to Perform the transformation of electrical energy into mechanical energy (torque and velocity). PMSM are Very efficient, High power density and FOC achieves accurate torque control.

4.7 Current Feedback and Clarke & Park Transformations

Alpha-Beta Block:

Takes 3-phase currents (ia, ib, ic) and converts them to the 2-phase stationary frame (αβ) using Clarke transformation.

Alpha-Beta to dq (Park Transformation):

Rotates αβ currents into rotating frames of dq. Decouples torque and flux control to increase system performance.

Output: i_q, i_d as feedback in control loops.

4.8 Feedbaclk loop
Real-time current feedback for the PID controllers. Ensures closed-loop control of motor currents to match the command values from the longitudinal driver.

4.9 Reasons for Using This Architecture in EV Applications
Accurate Torque Management can be done. The q-axis manages torque and the d-axis is set to zero for best performance. PMSMs work well, and FOC cuts down on waste by keeping the stator current vector just right. PID controllers give fast responses to changes.
Better Inverter Use: SVPWM makes the most of the DC bus and cuts down on harmonic losses

4.10 . Potential Improvements for Future Study
Switching out PID for cutting-edge controllers (like Model Predictive Control). Putting in place sensorless FOC that uses estimators to figure out rotor position. Adding regenerative braking control to the long-ways driver logic [10].

4.11 . Field Oriented Control Algorithm:
- Decouple torque and flux control: By aligning the stator current with the rotor magnetic field.
- Improve dynamic performance: Providing rapid response to changes in torque or speed.
- Enable high efficiency: Especially under variable speed and load conditions.
- This is achieved by transforming the three-phase stator currents into two orthogonal components:
- d-axis (direct axis): Aligned with the rotor magnetic flux.
- q-axis (quadrature axis): Perpendicular to the d-axis and responsible for torque generation.
- The control objective is typically to maintain i_d=0 (in surface-mounted PMSMs), and control iq to regulate the torque.

5. RESULTS AND DISCUSSION

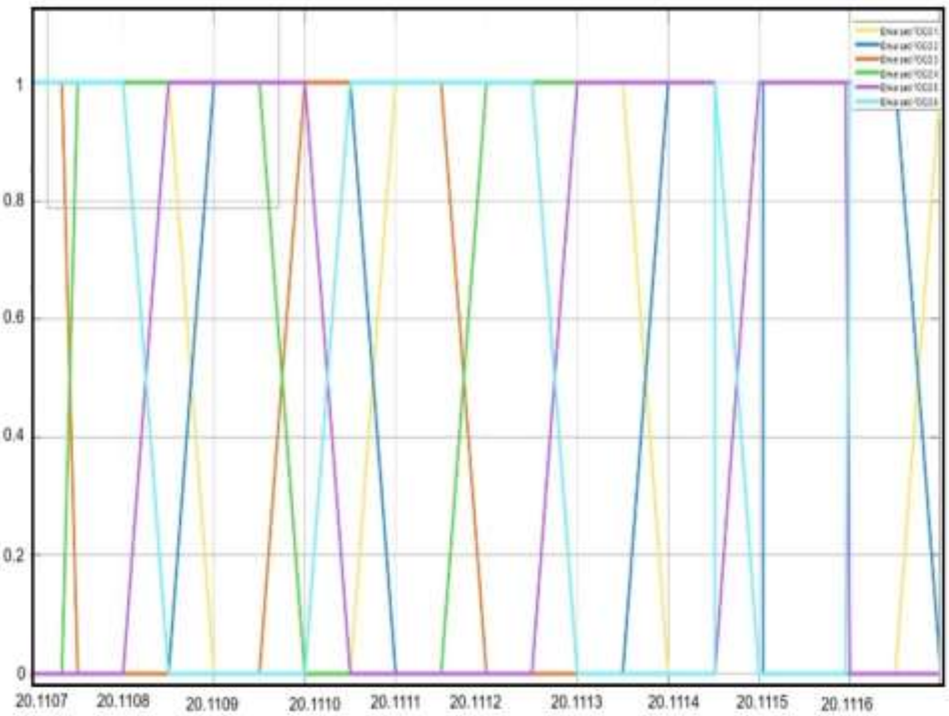

Fig.4: Pulses Generated by the SVPWM
The output of the pulses generated by the SVPWM for the switching of the inverter is shown in Figure 4. The SVPWM signal generated and the dq-axis currents (Id and Iq) generated by the FOC controller are shown in Figure 5. From the results, it can be interpreted that the SVPWM signals exhibit a high-frequency switching pattern with proper synchronization among phases. The Iq current is following the torque demand profile with minimal delay and ripple.

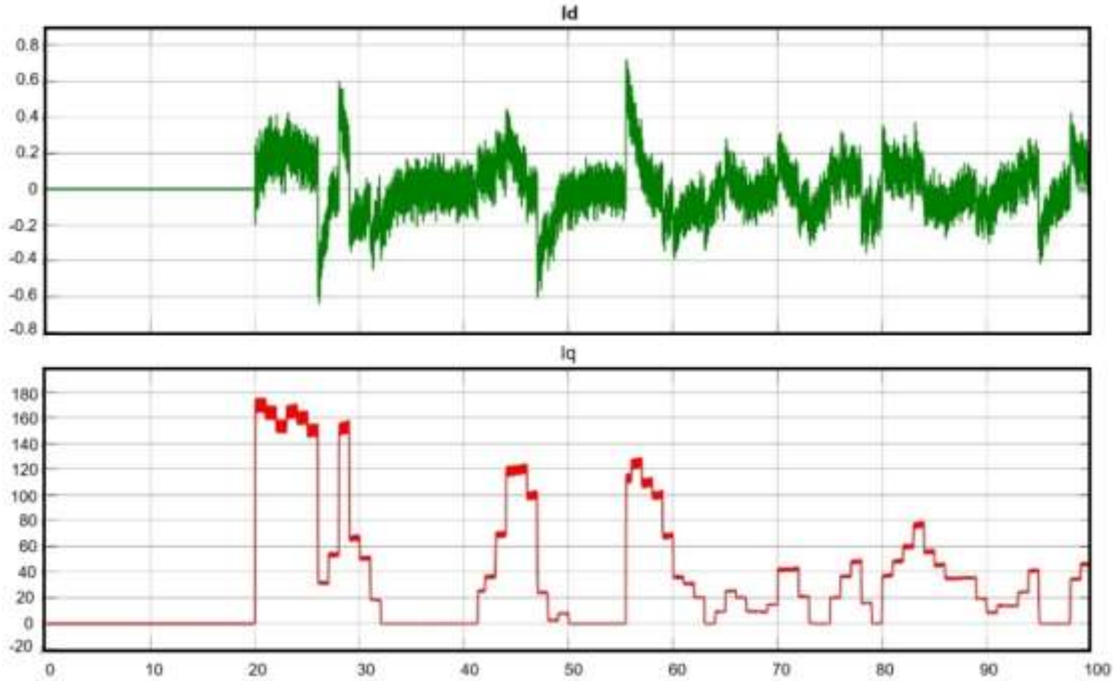

Fig.5: i_d *and* i_q wave forms

The switching signal is generating an average output vector in synchronous to the voltage vector in d-q plane. From this it can be inferred that the inverter is delivering the required voltage and current to the motor. The minor oscillations are due to the FOC control and can be ignored for general purpose drives. In the Figure 6, the speed, torque, and the SOC curves throughout the driving cycle are represented. A smooth and steady increase from standstill to the target speed can be observed in the motor speed. The torque profile is consistent and is proportional to the torque generated by the Iq current. The torque is consistent throughout and any initial spike in the torque can be attributed to the vehicle acceleration. The small ripples are a resultant of harmonics in the inverter and the magnetic cogging in the motor.

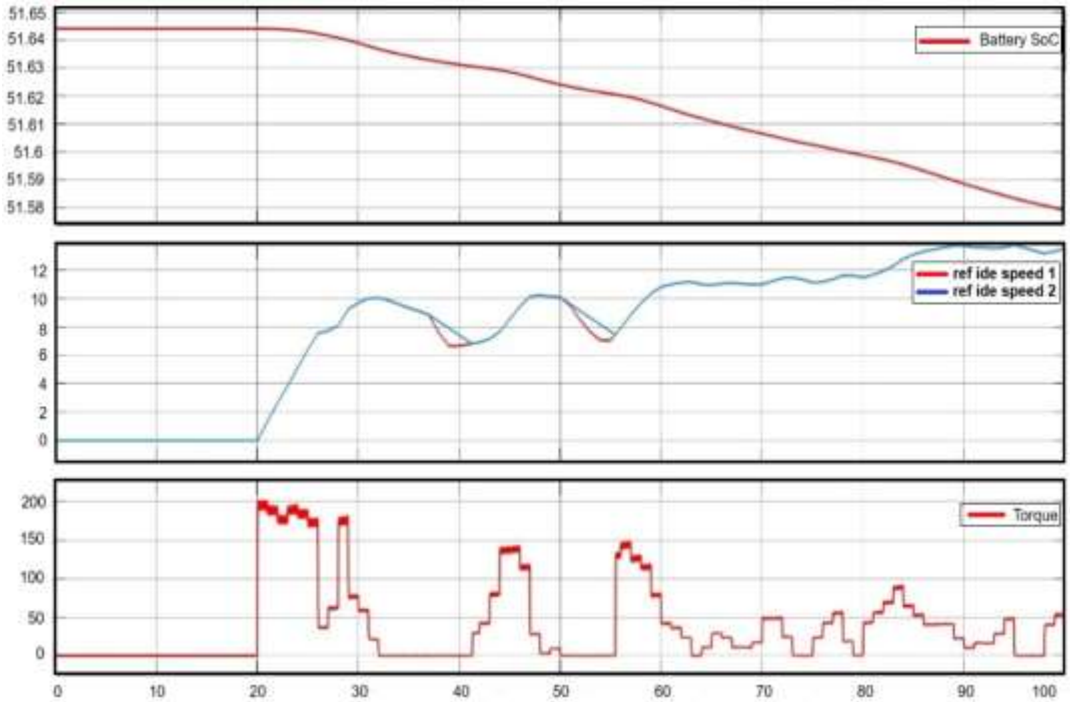

Fig.6: Characteristics of Battery SoC, Speed and Torque

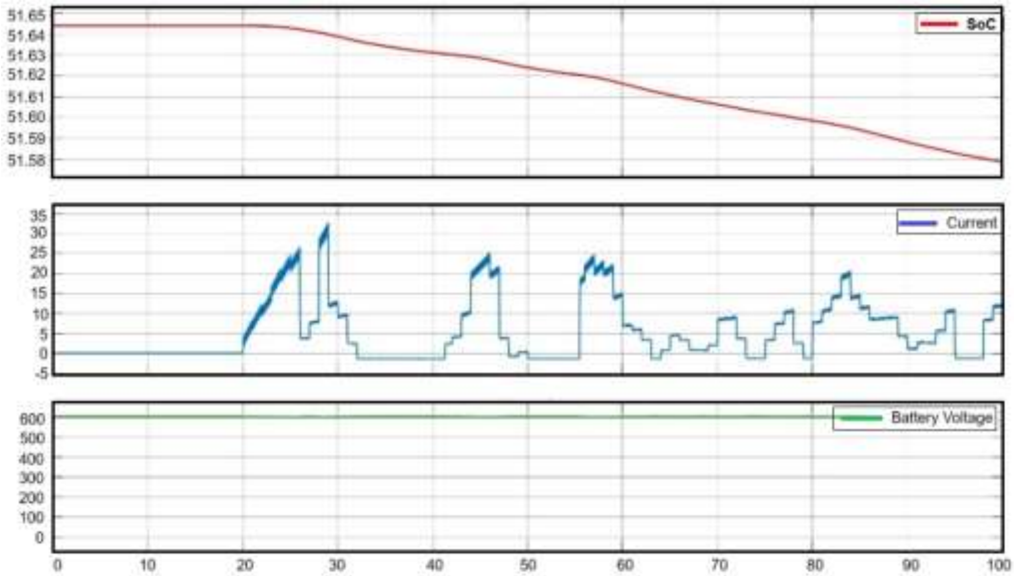

Fig.7: Battery SoC, Current and Voltage

The battery parameters current, voltage, and SOC are shown in Figure 7. The initial spikes are due to the acceleration, and is a resultant of surge in torque demand. As the vehicle tranists from cruise mode, the current stabilizes and achieves a lower and nearly constant energy. This results are in alignment with the real-world applications in which peak power demand is expected during acceleration and remains constant during steady speed. The SoC mataches the speed curve and remains within the specified limits through out the operation. The constant voltage significes the appropriate choice of the battery and efficient load management.

CONCLUSION:

This study presents an in-depth exploration of Field-Oriented Control (FOC) applied to Permanent Magnet Synchronous Machines (PMSMs) for use in Electric Vehicles (EVs). By referencing the Indian Drive Cycle (IDC) to simulate typical driver patterns in a rear-wheel-drive configuration, the work demonstrates the effectiveness of FOC in enhancing overall system performance. Through decoupled closed-loop regulation of the direct-axis i_d and quadrature-axis $i_q$currents, FOC ensures optimal synchronization between the rotor and stator magnetic fields. This coordination leads to better energy efficiency, more accurate torque and speed regulation, smoother vehicle dynamics, and reduced power loss. The analysis from the MATLAB simulation confirms that the suitability of PMSM based electrical vechile drive train for EV applications. The motor exhibited fast dynamic response and achevied the expected drive torque output under varying conditions. It can be concluded that their high efficiency, excellent dynamic behaviour and compartability with advanced control systems makes PMSM an ideal choice for EV applications. As a future scope, inclusion of harmonic suppression filters or predictive torque control will be implemented to reduce torque ripples. A regenerative setup can also be included to enhance the SoC recovery during deceleration.

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